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Russell V. Parrish
and Steven P. Williams

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Determination of Depth-Viewing Volumes for Stereo Three-Dimensional Graphic Displays

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Summary

Three-dimensional ("real-world") pictorial displays incorporating "true" depth cues via stereopsis techniques offer a potential means of displaying complex information in a natural way to prevent loss of situational awareness and provide increases in pilot/vehicle performance in advanced flight display concepts. Optimal use of stereopsis cueing requires an understanding of the depth-viewing volume available to the display designer. A knowledge of where and how accurately a subject perceives the depth cues placed within the depth-viewing volume is essential. This report presents suggested guidelines for the depth-viewing volume from an empirical determination of the effective region of stereopsis cueing (at several distances between the viewer and the cathode ray tube (CRT) screen) for a time-multiplexed stereopsis display system. The results provide the display designer with information that will allow more effective placement of depth information to enable the full exploitation of stereopsis cueing.

Data were gathered comparing perceived depth via subject judgment (from physical probe placements) against computed depth (from lateral disparity calculations) at several viewer-CRT screen distances. In addition to indicating the available depth-viewing volume at each screen distance for use by display designers, the data revealed the fact that increasing the viewer-screen distances provides increasing amounts of usable depth but decreases the fields of view. This fact strongly suggests a stereopsis hardware system incorporating larger screen sizes or collimation optics to maintain the field of view at a desirable level while providing a much larger stereo depth-viewing volume.

Introduction

Current electronic display technology can provide high-fidelity ("real-world") pictorial displays under flicker-free conditions that incorporate "true depth" in the display elements. Advanced flight display concepts that embody true three-dimensional (3-D) images of synthetic objects or scenes (computer-generated) are being conceived and evaluated at the NASA Langley Research Center and at the Air Force Wright Research and Development Center (refs. 1-6). Innovative concepts are sought that exploit the power of modern graphics display generators and stereopsis cueing not only in situation-awareness enhancements of pictorial displays but also in displays for the declutter of complex informational displays and in providing more effective alerting functions to the flight crew.

The intuitively advantageous use of a three-dimensional display of three-dimensional information, rather than the conventional two-dimensional display of such information, has been investigated for years within the flight display community (refs. 7-13). These efforts have been particularly intense for helmet-mounted head-up display applications because the display of stereopsis cueing information is readily available with binocular helmet systems (refs. 7-10). Additional investigations utilizing electronic shutters or polarized filters, rather than helmet optics, to present separate left- and right-eye views have also been conducted (refs. 1-4, 5, 6, and 10-13).

The goal of this effort was to provide the display designer with an understanding of the effective depth-viewing volume available to allow full exploitation of stereopsis cueing in advanced flight display concepts. The effective viewing volume would be that space in which the pilot/observer would be able to comfortably and clearly perceive objects (including text) to be located at an intended depth (the depth desired by the designer) with some degree of accuracy. Thus, optimal use of stereopsis cueing is presumed to require a knowledge of where and how accurately a subject perceives the depth cues placed within the depth-viewing volume, especially for pictorial flight display applications, where accurate perception of depth cues may be critical for flight control. An empirical determination of the effective region of stereopsis cueing for a time-multiplexed stereopsis display system is reported. Data were gathered comparing perceived depth via subject judgment (from physical probe placements) against computed depth (from lateral disparity calculations) at several distances between the viewer and the cathode ray tube (CRT) screen. Based on these empirical results, guidelines for a practical depth-viewing volume are suggested.

Symbols, Abbreviations, and Definitions

Symbols

α	angular lateral disparity, rad
D	distance between observer and screen, in.
d	distance between screen and object being presented via stereopsis techniques, in.
i	interocular distance, in.
y	lateral disparity, in.

Abbreviations:

CRT	cathode ray tube
FOV	field of view
RGB	red-green-blue

Definitions:

accommodation	a change in focus accomplished by a change in the lens thickness of the eye, which changes the focal length
angular lateral disparity	the difference in convergence angles required to fixate two points; it relates to the depth between the two points
binocular	viewed by both eyes
binoptic	both eyes being presented with the same image
depth-viewing volume	volume provided by stereopsis display techniques, encompassing space both in front of and behind the CRT screen. In this paper, determination of this volume concerns only the depth component, excluding consideration of the height and width components.
diplopia	double vision, a condition induced by the use of large lateral disparities
interocular distance	lateral distance between the two retinas of the eye, in.
lateral disparity	horizontal displacement of an object from the center of the screen to a stereopair presentation required to place the object at some depth from the screen
lateral retinal disparity	positional differences occurring in two different views of the visual scene from viewpoints separated by a lateral distance that scales the interocular distance between the two retinas of the eye

monoscopic	viewed by one eye only
Panum's area	range of lateral disparities that can be fused around a fixation distance without eye movements
stereopsis cueing	display of information utilizing the depth dimension and introduced by means of lateral disparity
vergence	rotational movement of the eye to align each eye with a point in the scene. In "real-world" viewing, the muscles rotate the eyes outward or inward so that the lines of sight of both eyes intersect at the depth distance of the object being fixated.

Stereopsis Background

High-fidelity three-dimensional displays that incorporate "true" depth in the display elements are provided by displaying to each eye a disparate view of the visual scene by means of various display hardware systems such that the right eye sees only the right-eye scene and the left eye sees only the left-eye scene. These hardware systems include refracting or reflecting stereoscopes and systems that incorporate electronic or mechanical shutters, or polarized or color filters. Helmet systems depend on a direct presentation of each eye view.

In any case, regardless of the display hardware system, graphics software is necessary to create the left- and right-eye stereopair images. The graphics generation computer performs this task, resolving the single-viewpoint visual data base stored within it into the desired stereo pair. Figure 1 illustrates the parallax concept employed to produce objects behind the monitor screen via stereo pairs. Figure 2 illustrates the concept as it is employed to produce objects at various depths. The heavy horizontal line represents the screen of the display monitor. To present an object that appears at the depth of the screen, the object is drawn in the same location for both stereopair views. For objects to appear behind the screen, the object is displaced to the left for the left-eye view and to the right for the right-eye view (with the displacement reaching a maximum value to place an object at infinity). For objects to appear in front of the screen, a displacement to the right is used for the left-eye view and to the left for the right-eye view.

Depth Cues

In binoptic or monoscopic displays of perspective real-world scenes, a great deal of depth information is provided by such cues as linear perspective, relative size, shape, object interposition, motion perspective, motion parallax, texture gradients, shading, etc. Stereoscopic displays of such scenes add both the cues of lateral retinal disparity and the cues of muscular movement and tension associated with vergence. In stereoscopic displays, the introduction of lateral disparity initiates vergence to create a perceived depth. (See fig. 1.) Although lateral disparity and vergence are usually interdependent and nonseparable, the physiological cues associated with the eye muscles controlling the vergence movements are separate cues from those of lateral disparity in the psychophysical/physiological literature (refs. 14-20). Stereoscopic displays thus produce both the muscular cues and the disparity/vergence cues associated with depth perceptions.

Other depth cues that are present in real-world viewing are changes in focus (accommodation) and pupil size (although pupil size remains constant for object distances greater than about 3 ft). In stereoscopic displays, the viewing distance that affects both accommodation and pupil size is the screen distance (the distance between eye and image source), which remains constant. Thus, the major depth cue missing in the synthetic generation of stereoscopic displays is the change in accommodation with fixation point depth, and it is indeed a major lack because accommodation and convergence are highly interactive. For a fixed accommodation distance, there is a limited range of vergence conditions that will result in comfortable, clear, fused, single vision. This implies that for a given screen distance for a stereoscopic display, there are limits to the amount of lateral disparity that is usable by the display designer. These limits require the display designer, in the case of real-world pictorial displays, to map the depths in the real-world to the depths available with the stereo display system. Figure 3 illustrates the mapping of a real-world scene to the stereo viewing volume.

Relationship Between Lateral Disparity and Depth

Figure 4 presents the geometric relationship between lateral disparity and depth for objects appearing behind the screen, which is the case with positive disparity (i.e., divergent, or uncrossed, disparity). By similar triangles,

$$y = \frac{id}{2(d+D)}$$

Objects appearing in front of the screen obey the same equation, but with negative disparity (i.e., convergent, or crossed, disparity). The maximum positive disparity considered allowable under any circumstances is one-half the interocular distance, which would produce parallel lines of sight (for objects at infinity). The maximum negative disparity would be limited for objects along the centerline to one-half the width of the screen. However, these extremes will far exceed the limits for comfortable, usable viewing.

The limits for lateral disparity have been examined and reported in the psychophysical/physiological literature (refs. 14-20). For small values of disparity, the perceived depth of an object varies linearly with disparity, and observers are able to judge the depth of objects accurately. At larger values, a point is reached at which single vision, or fusion of the left and right images, is lost and double vision (diplopia) occurs. (The area of single vision without eye movement is known as Panum's fusional area.)

In reference 15 (p. 393) Poggio and Poggio state:

"There is a vast literature, and a correspondingly large amount of data, on Panum's fusional area, and almost as much disagreement on its properties and even its precise definition."

Figure 5 provides the results of solving the disparity equation for the three values of screen distance used in this study. (The particular values for screen distance will be discussed later.) The curves were calculated for an interocular distance of 2.5 in. and they intersect the abscissa (zero disparity) at each appropriate screen distance. (The actual disparities used in the experiment were calculated based on the individual subject's interocular distance.) The negative disparity values represent objects appearing in front of the screen, and the positive values represent objects appearing behind the screen.

For each screen distance, and for objects appearing both in front and behind (negative and positive cases, respectively), there is a practical limit to the amount of lateral disparity that is considered usable. If one uses the suggested value of ± 40 minutes of arc for the angular lateral disparity limits of Panum's fusional area (ref. 14, p. 1084), the depth limits for the three screen distances in table I can be calculated by using the following equation (from ref. 14, p. 1063):

$$d = aD^2(i - aD)$$

These limits are suggested for observers with eye movements restricted by fixation at screen distances.

As a result of the size of the CRT screen available, a screen distance of 19 in. was chosen for the study in reference 4 because that distance yielded a horizontal field of view (FOV) of 40°, a FOV that is conventionally used in flight simulation. However, the stereo depth envelope, or viewing volume, suggested in table I is very small. Indeed, the depth envelope successfully utilized in reference 4 for mapping was computed to extend to at least 28.5 in., or 9.5 in. behind the screen. Based on this experience, a 19-in. distance was chosen as the base screen distance for the present study. To investigate possible increases in the depth envelope, larger screen distances (chosen as multiples of the base distance) were to be considered at the expense of decreasing the FOV.

For viewer comfort, the designer-usable limits should fall inside the values of disparity at which single vision is lost and double vision (diplopia) occurs. Aside from the comfort aspect of the "in-front" and "behind" limits, there is the issue of the ability of an observer to judge the depth of objects accurately. Reference 14 (p. 1112) states that diplopia does not interfere with "accurate localization in depth".

The depth-viewing volume suggested by the calculations presented in table I for the 19-in. screen distance is much more restrictive than the volume utilized in reference 4. In light of the confusion on the properties and definition of Panum's fusional area, and because a much larger depth-viewing volume was utilized successfully in reference 4, an effort was made to determine the usable depth-viewing volume available for the three chosen screen distances. This effort involved the presentation of an object to an observer at a computed depth via the stereoscopic display technique using a one-to-one mapping of the real-world to the stereo viewing volume. The curves of figure 5 are the transformations used to achieve this one-to-one mapping. The observer then positioned a physical probe (a real-world probe) to the distance that represented where the image was perceived to be.

Experimental Apparatus

The experiment was conducted utilizing a graphics display generator and associated stereo software, a display format, stereo display system hardware, and an observer station.

Graphics Generation Hardware and Software

The graphics generation hardware consisted of a Silicon Graphics IRIS 70 GT. Graphics software within the graphics generator was used to generate the stereo pairs with the required lateral disparity.

First, left-eye and right-eye coordinate systems were created as offsets from the viewer coordinate system of the visual scene. Clipping was then employed to limit each eye view to the display surface boundaries. Finally, simple perspective division was used to transform the three-dimensional viewing volumes to two-dimensional viewports, whose centers are offset from the center of the display screen by one-half the maximum-allowed lateral disparity (used to represent objects at infinite distance).

Visual Display Format

The display format utilized in the depth-determination task consisted of three elements: (1) a horizon line separating a blue sky from a brown Earth, as typically used in electronic attitude display indicators; (2) a single vertical rod that was always located at screen depth for reference purposes in the middle of the display monitor; and (3) a duplicate vertical rod that was located at the calculated depth from the screen by means of lateral disparity in the stereoscopic display. The latter vertical rod, which was used as the depth target, was positioned such that the leftmost image of the stereo pair never was positioned off the screen. (The virtual image produced by the stereo pair was always located 2.5 in. from the left side of the CRT monitor.) The horizon line was banked to the left by 3° and was presented with a lateral disparity of $i/2$ for each subject so that it could conceptually represent infinity. The two vertical rods were identical in size, regardless of the relative depths, such that no perspective cues were available. Figure 6(a) illustrates the full-screen display format (as would be observed by a subject).

Stereo Display System Hardware

The stereo display system hardware operated on the video signals supplied by the graphics display generation system. These video signals presented a noninterlaced frame at 60 Hz consisting of both the left- and right-eye stereo-pair images. (Fig. 6(b) presents the display as drawn by the graphics generation system in a stereo-pair arrangement.) The stereo display system hardware (fig. 7) separated the left- and right-eye scenes and presented each alternately at 120 Hz; the scenes spread across the entire monitor screen (time-multiplexed stereo, resulting in a loss in vertical resolution of 50 percent, as shown in fig. 6(a)). A screen-mounted liquid crystal shutter was placed in synchronization with the stereo pair such that with polarized glasses, the right eye saw only the right-eye scene and the left eye saw only the left-eye scene, each at 60 Hz without flicker. The stereo visual system hardware was developed by the StereoGraphics Corporation (ref. 21).

Observer Station and Task

The observer station consisted of a chair, a headrest (to ensure that the observer remained at the required screen distance), and two different physical probes for matching perceived depth of an image with actual depth of a probe. For images perceived as being behind the screen, the probe was a movable indicator mounted on a pulley/clothesline type of apparatus. The observer's task was to position the movable indicator to an actual depth behind the screen that the observer believed to match the perceived depth of the image presented on the CRT screen. (See fig. 8.) The movable indicator was mounted such that it moved along the left side of the CRT without the observer's view of the indicator being obstructed by the monitor. Therefore, the observer was not forced to move his head to view either the image or the probe, thus ensuring a maintenance of accurate screen distance.

To locate images that were perceived as being in front of the CRT screen, the observer held a rod horizontally in front of the screen which had a pencil mounted vertically at the end of the rod. Placement of the pencil probe was therefore intrusive to the stereoscopic display, whereas the "behind-screen" probe did not impinge upon the display. Both probes required the observer to adjust his accommodation cues from the screen distance to the probe distance. These changes in accommodation between screen and probe were expected to result in more accurate distance judgments for both the real and the virtual objects. A method of placement for the "behind-screen" probe within the stereoscopic display volume (intrusive) would have been desirable, but the observers were able to function with the experimental setup as described, and the setup is not believed to have affected the results.

Experimental Procedure

Four subjects were presented with randomized computed depths, with four replicates of each depth position occurring during the data collection session. Three sessions, one for each screen distance, were held for each subject. The initial position of the depth probe was randomized before the presentation of the next depth condition to avoid any possible hysteresis effects. For observer convenience, all "behind-screen" conditions were tested as a group and all "in-front" conditions were tested as a group so that incessant probe changes did not occur. This grouping is not believed to have affected the data.

Results and Discussion

Figures 9, 10, and 11 present the 95-percent confidence intervals for perceived depth from the dis-

play screen as a function of the computed depth from the screen from the lateral disparity values for three screen distances (19 in., 38 in., and 57 in., respectively). The data represent the results of 800 trials, with 4 subjects judging 4 repetitions at each depth position. A straight line with a slope of 1 is also presented in the figures and represents the ideal case of perceived depth coinciding with computed depth. For objects placed in front of the screen, the occurrence of severe object blurring limited the usable volume. Increasing the object depth (lateral disparity) in front of the screen resulted eventually in double vision. For objects placed behind the screen, the depth perceived was increasingly larger than that presented. That is, the farther the object was placed behind the screen, the larger the error became. This fact is true, at least, until the extremes of the computed depths examined in the experiment are reached. The size of the confidence intervals about the perceived depth means within these extreme regions is such that these regions are not usable for practical applications.

The range of computed depth for which perceived depth is somewhat accurate increases with increasing screen distance, as may be seen by comparing the curves of figures 9-11. Thus, a larger usable viewing volume is available for increasing screen distances for objects placed both in front of and behind the screen.

Figures 12-14 present the 95-percent confidence intervals for perceived depth error as a function of computed depth, with both normalized to the screen distance, for each of the three screen distances. Normalization of the data reveals similar slopes and intercepts for the three screen distances examined.

Subjects were much more accurate in their perceived depth estimates for the in-front images compared with the behind-screen conditions. This fact is not believed to have been influenced by the change in probe type for the in-front conditions or by the grouping of conditions. Thus, as objects are placed farther and farther in front of the screen, and closer and closer to the observer, they quickly begin to blur. Thus, although the distance judgments are more accurate, the usable volume in front of the screen is smaller than the usable volume behind the screen.

If one accepts an arbitrary criterion of comfortable, unblurred single vision in front of the screen and, equally arbitrarily, less than a 10-percent perceived depth error behind the screen, the usable depth-viewing volume falls between $-0.25D$ and $0.6D$ of the screen distance. (The 10-percent error criterion is marked with lines in figs. 9-11.) Thus, the normalization of the data from the individual screen distances provides suggested guidelines ($-0.25D$ and $0.6D$) for the depth-viewing volume for a generalized

screen distance D . Table II presents these limits for the screen distances examined along with the corresponding fields of view (FOV). These limits, which are much larger than those of table I, are suggested as guidelines for practical, usable depth-viewing volumes for stereopsis displays.

It should be noted that these limits define a volume in which multiple objects may be placed that have different convergence requirements. That is, simultaneous viewing of objects at different depths within the volume may not seem quite "right" to the observer even though comfortable fusion of both objects occurs. Careful design within the viewing volume for portions of the display that are desired to be viewed simultaneously must be exercised.

Several other interesting points, though not germane to the main purposes of this paper, are contained within the data. As seen in figures 9-11, near the extremes of the computed depths examined (when the confidence intervals about the means are rapidly deteriorating), the slopes of the mean curves become less than 1 and the errors become smaller and smaller. This fact is also revealed (perhaps more clearly) in the normalized error data in figures 12-14. As the image is placed farther and farther behind the screen, the positive slope of the perceived depth-error curve (ideally zero) eventually becomes negative. This phenomenon was not investigated further in this study as the region is beyond the recommended practical limits of usable depth. It may represent the limits of perceivable depth—that is, no matter how much farther an image is placed behind the screen, the observer still perceives it to be the same distance away, at least until diplopia occurs.

There is another slope change in each of the depth-error curves as computed depth passes from behind the screen to in front of the screen (passes through zero toward the negative values). This change in slope indicates the fact (previously discussed) that subjects were much more accurate in their perceived depth estimates for the in-front images. The limit to usable depth in front of the screen was not chosen based on perceived depth error, but rather on clear, comfortable vision. Furthermore, the experience reported in reference 4 with in-front images was that most pilots objected to images in the real-world pictorial displays that penetrated the cockpit area (the in-front area).

Concluding Remarks

Stereopsis cueing offers a potential means of displaying complex information in a natural way to prevent loss of situational awareness and to provide increases in pilot/vehicle performance in advanced

flight display concepts. Optimal use of stereopsis cueing requires an understanding of the depth-viewing volume available to the display designer. A knowledge of where and how accurately a subject perceives the depth cues placed within the depth-viewing volume is essential to enable effective displays for precision control tasks. In this report, the empirical determination of the effective region of stereopsis cueing for a time-multiplexed stereopsis display system provides the display designer with information that will allow more effective placement of depth information to enable the full exploitation of stereopsis cueing.

The normalization of the data from the individual screen distances provided suggested guidelines for the depth-viewing volume for a generalized screen distance. In addition to indicating this available depth-viewing volume for use by display designers, the data revealed the fact that increasing viewer-screen distances provide increasing amounts of usable depth, but with decreasing fields of view. This fact strongly suggests a stereopsis hardware system incorporating larger screen sizes or collimation optics to maintain the field of view at a desirable level while providing a much larger stereo depth-viewing volume.

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Table I. Calculated Depth Limits for Panum's Fusional Area for
Three Screen Distances

Screen distance, in.	"In-front" limit, in.	"Behind" limit, in.	Depth envelope, in.	Field of view, deg
19	17.16	20.54	3.38	40
38	29.84	43.71	13.87	20.6
57	36.42	68.95	32.53	13.8

Table II. Practical Depth Limits for Three Screen Distances

Screen distance (D), in.	"In-front" limit ($-0.25D$), in.	"Behind" limit ($0.6D$), in.	Depth envelope ($0.85D$), in.	Field of view, deg
19	14.2	30.4	16.2	40
38	28.5	60.8	32.3	20.6
57	42.8	91.2	48.4	13.8

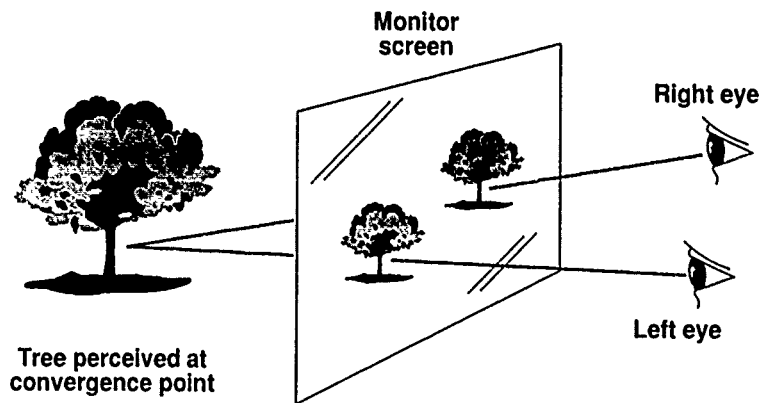


Figure 1. Concept for introducing depth via stereo-pair display.

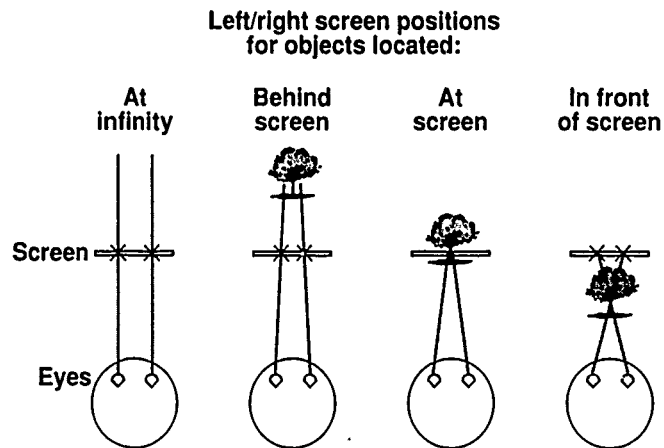


Figure 2. Top view of geometric principle for producing left- and right-eye views.

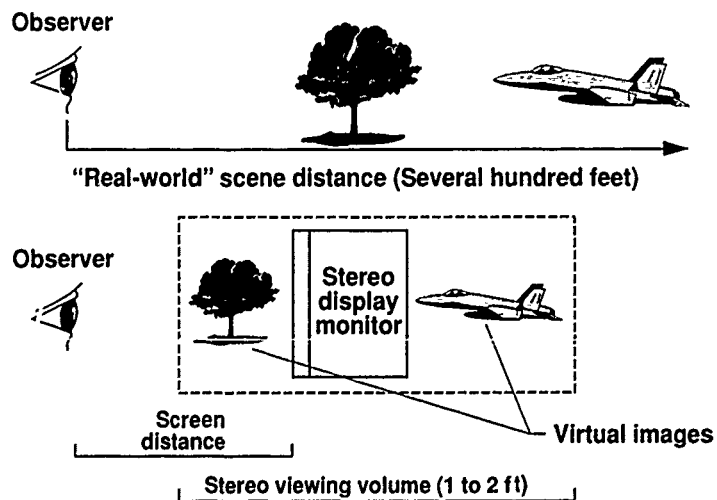


Figure 3. Mapping of "real-world" scene to stereo viewing volume.

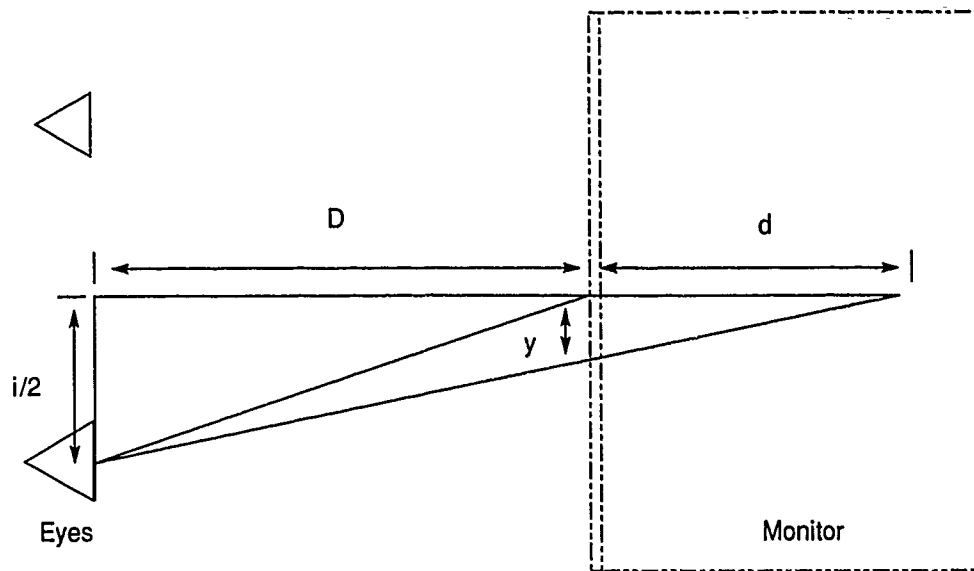


Figure 4. Overhead view of subject and monitor showing relationship between lateral disparity and depth.
 i = Interocular distance; D = Screen distance; d = Depth; y = Lateral disparity.

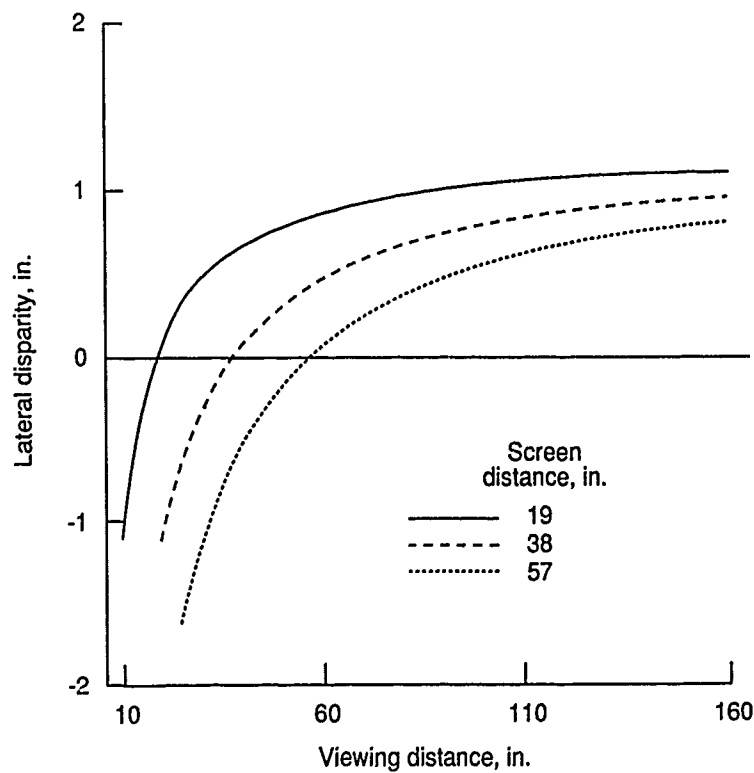
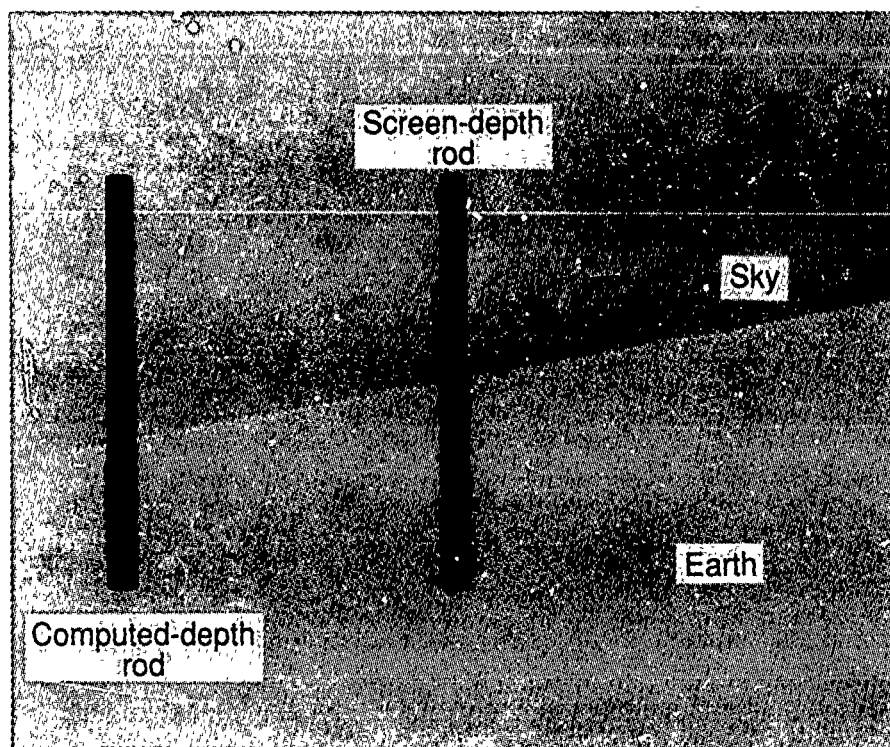
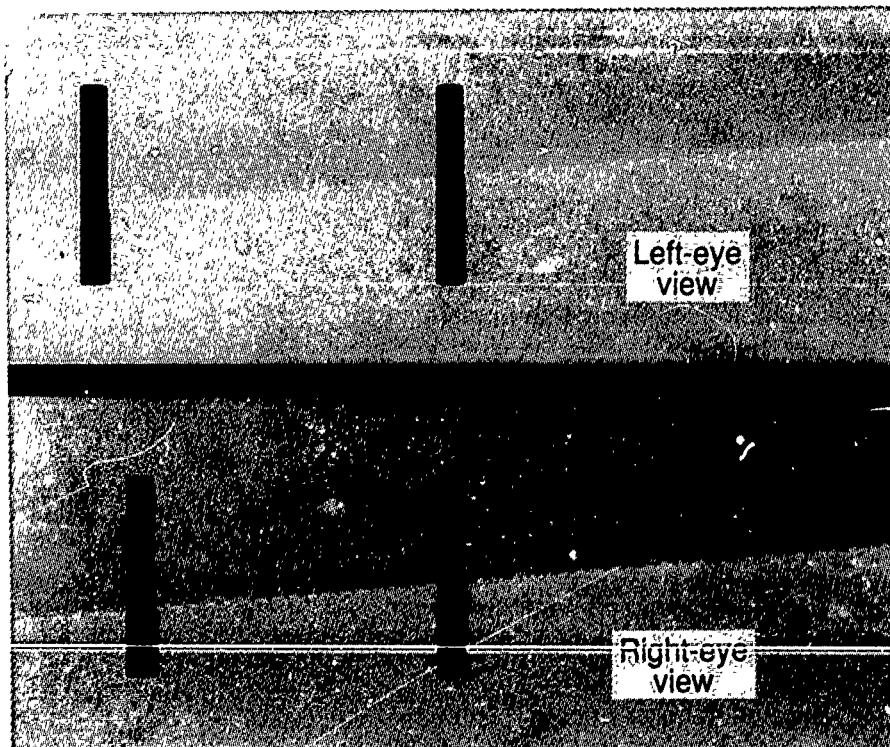


Figure 5. Lateral disparity versus image locations for three separate screen distances.



(a) Full-screen nonstereo view.



(b) Stereo-pair view.

Figure 6. Display format.

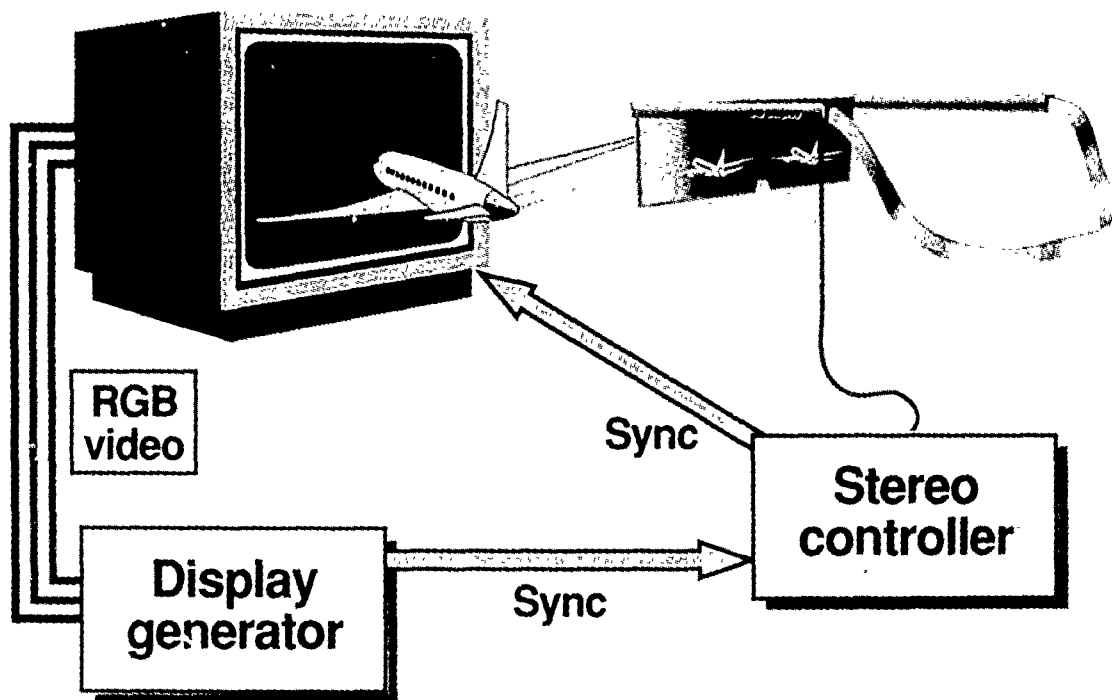


Figure 7. Concept of stereo 3-D display system hardware.

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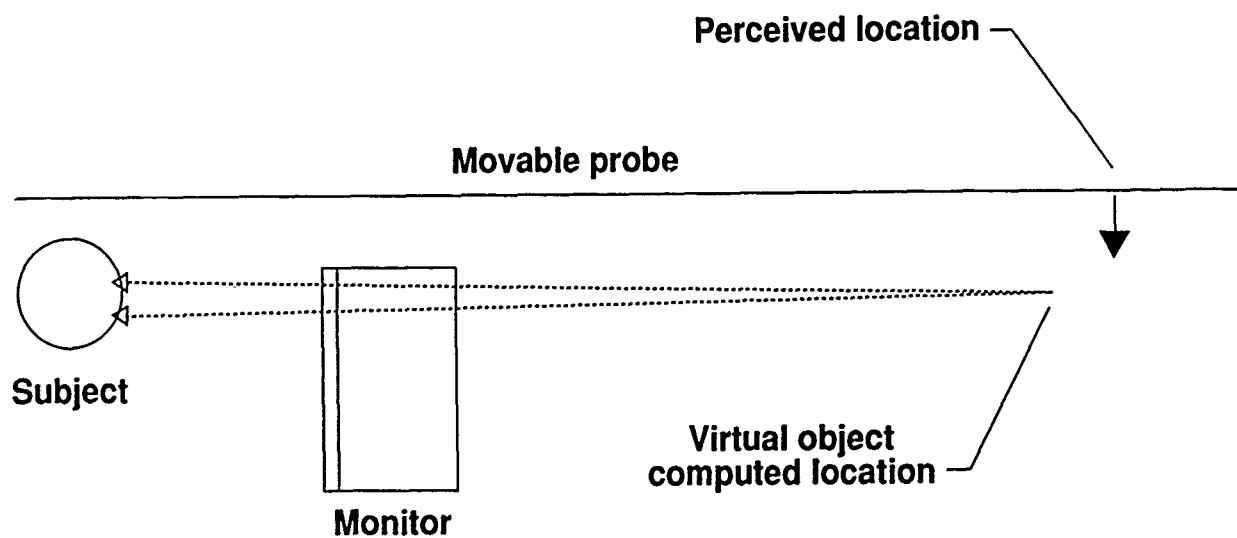


Figure 8. Top view of experimental apparatus.

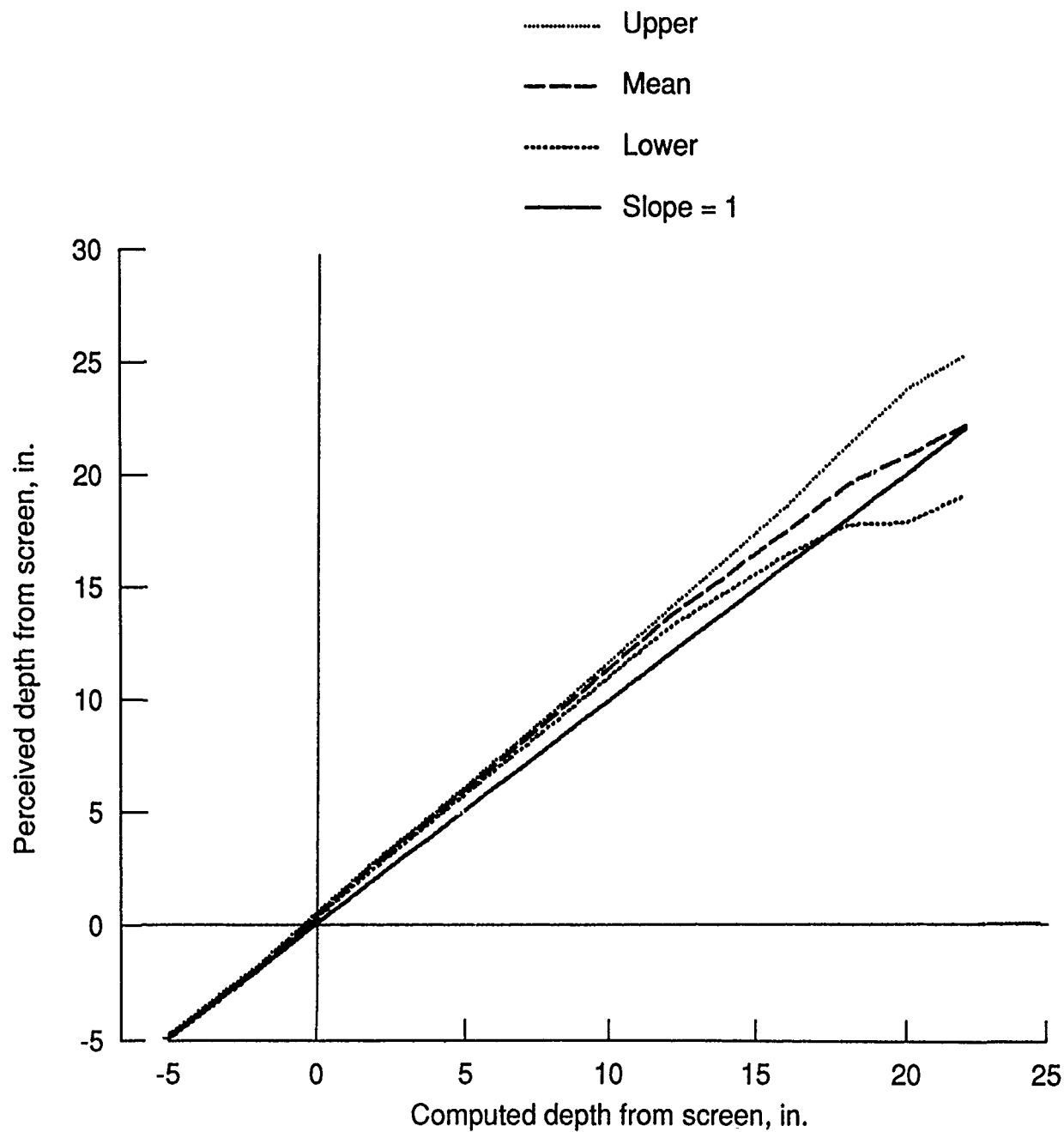


Figure 9. A 95-percent confidence interval for perceived depth as function of computed depth for screen distance of 19 in. (16 trials per point).

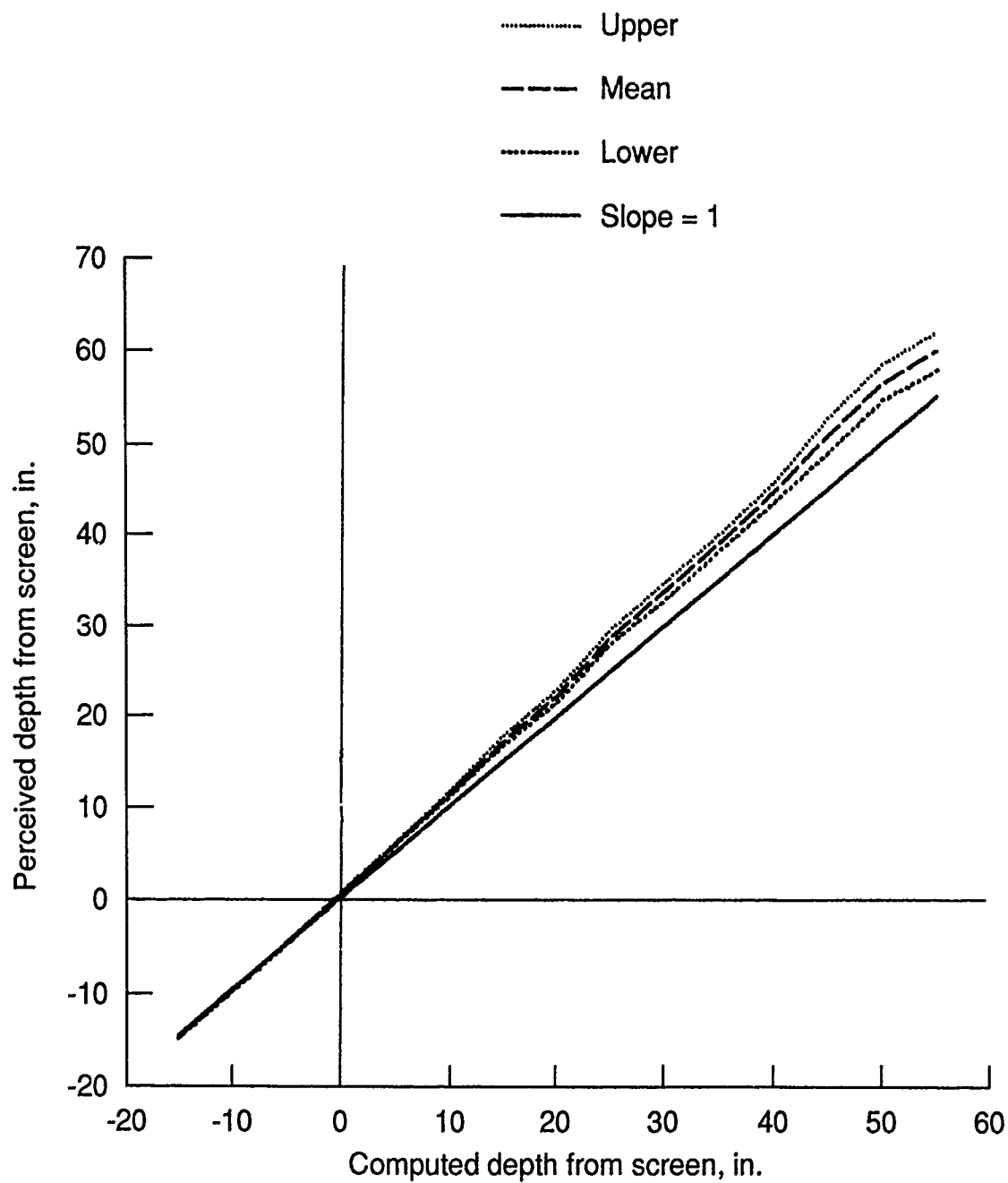


Figure 10. A 95-percent confidence interval for perceived depth as function of computed depth for screen distance of 38 in. (16 trials per point).

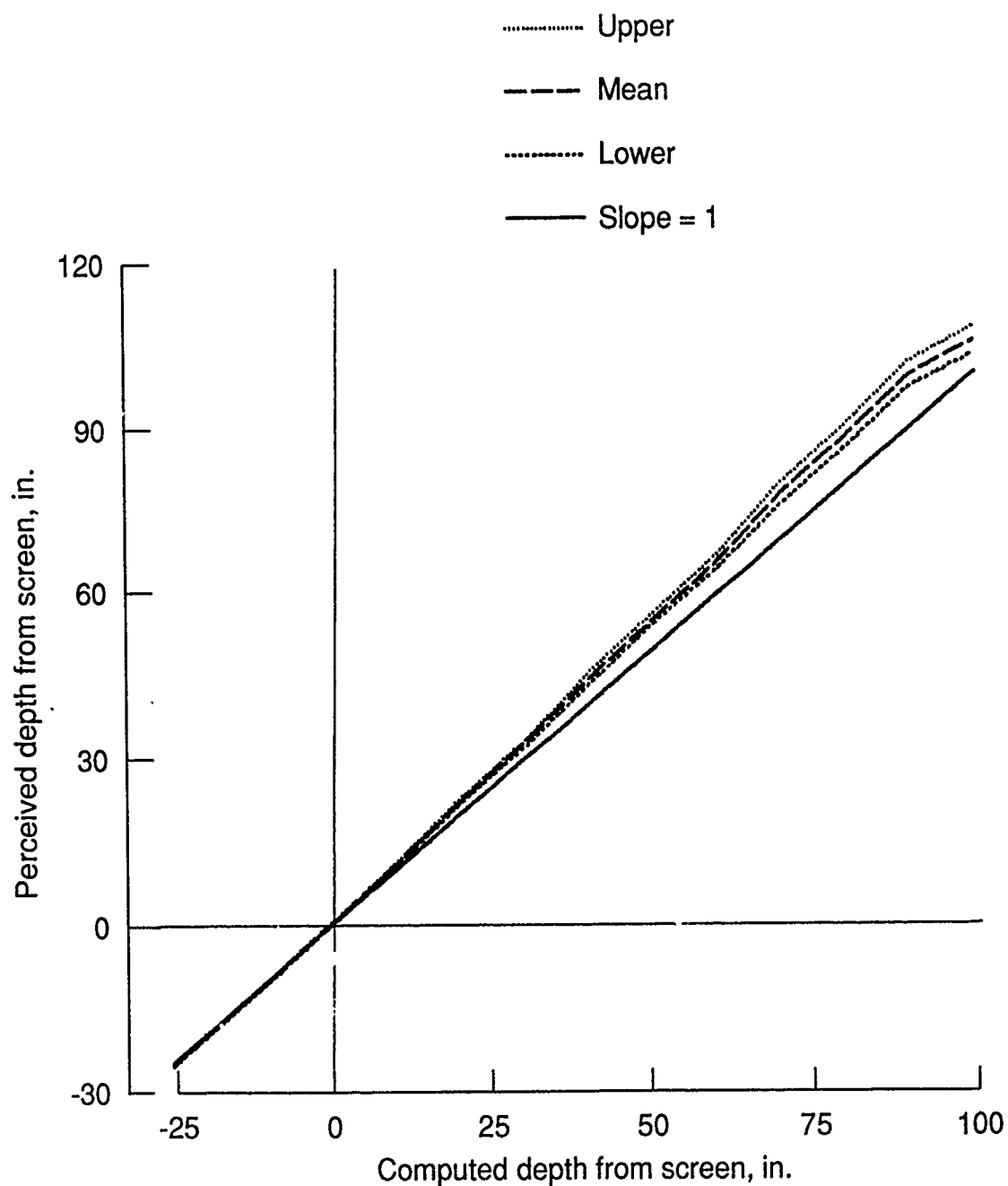


Figure 11. A 95-percent confidence interval for perceived depth as function of computed depth for screen distance of 57 in. (16 trials per point).

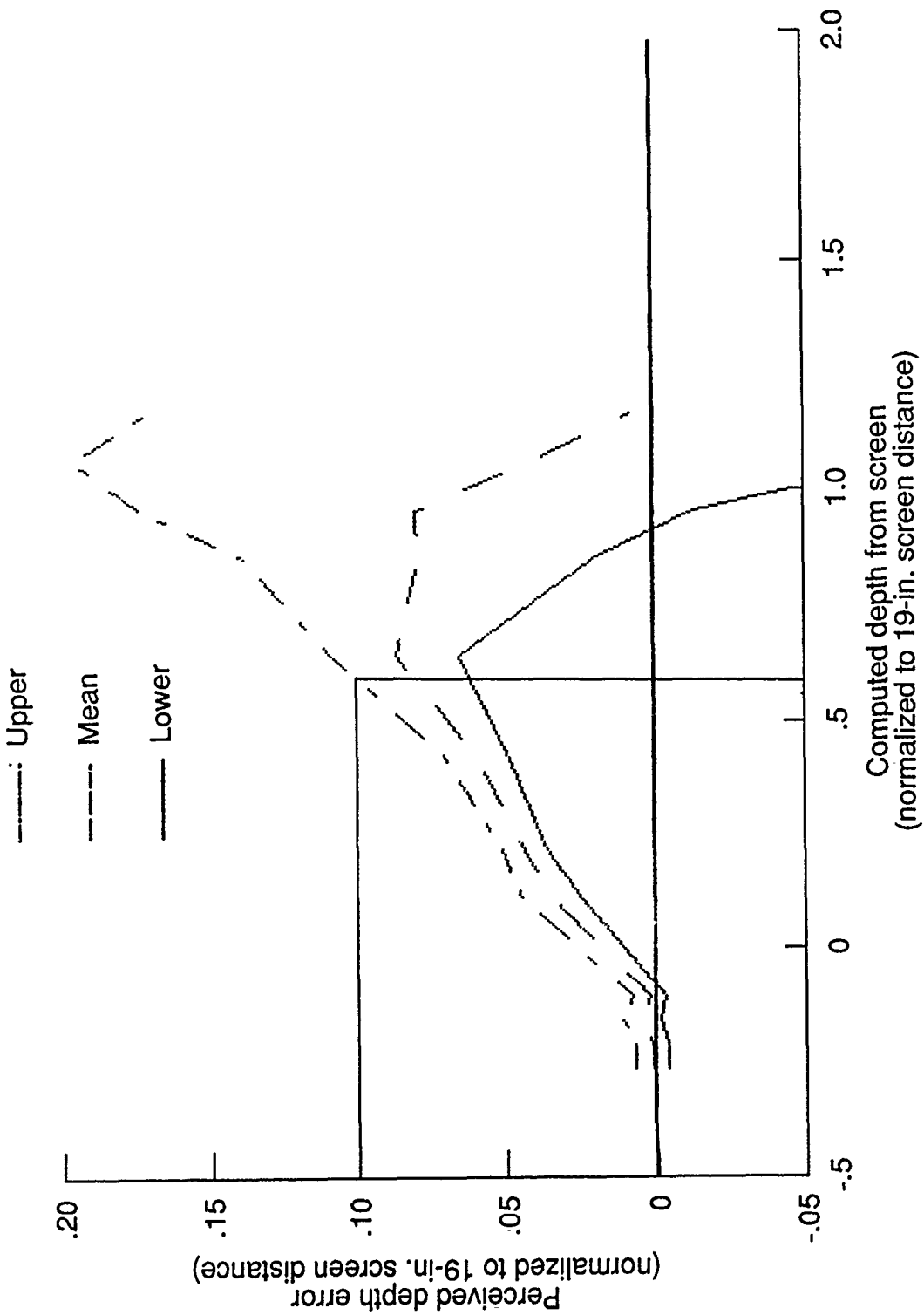


Figure 12. A 95-percent confidence interval for perceived depth error as function of computed depth for screen distance of 19 in.

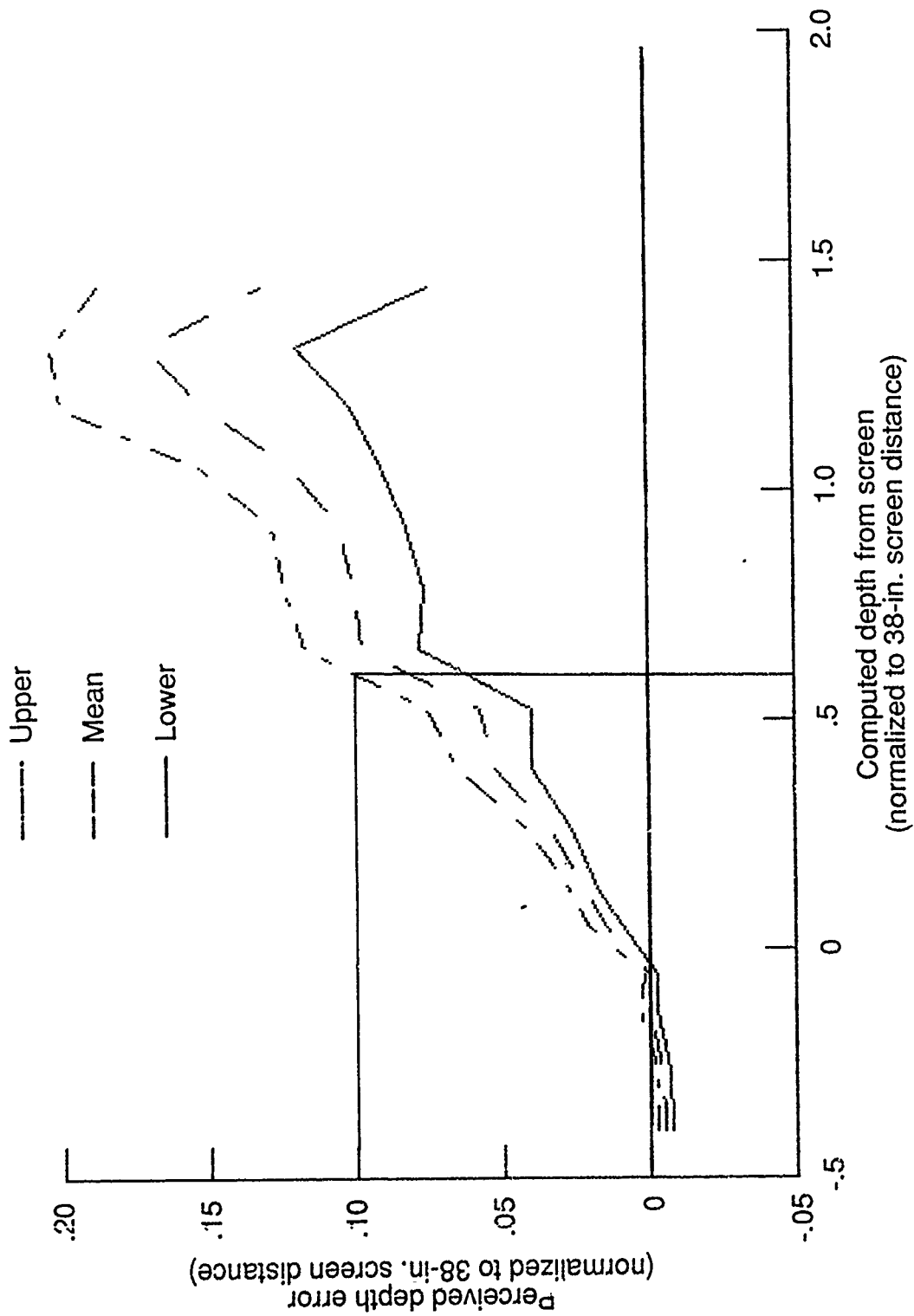


Figure 13. A 95-percent confidence interval for perceived depth error as function of computed depth for screen distance of 38 in.

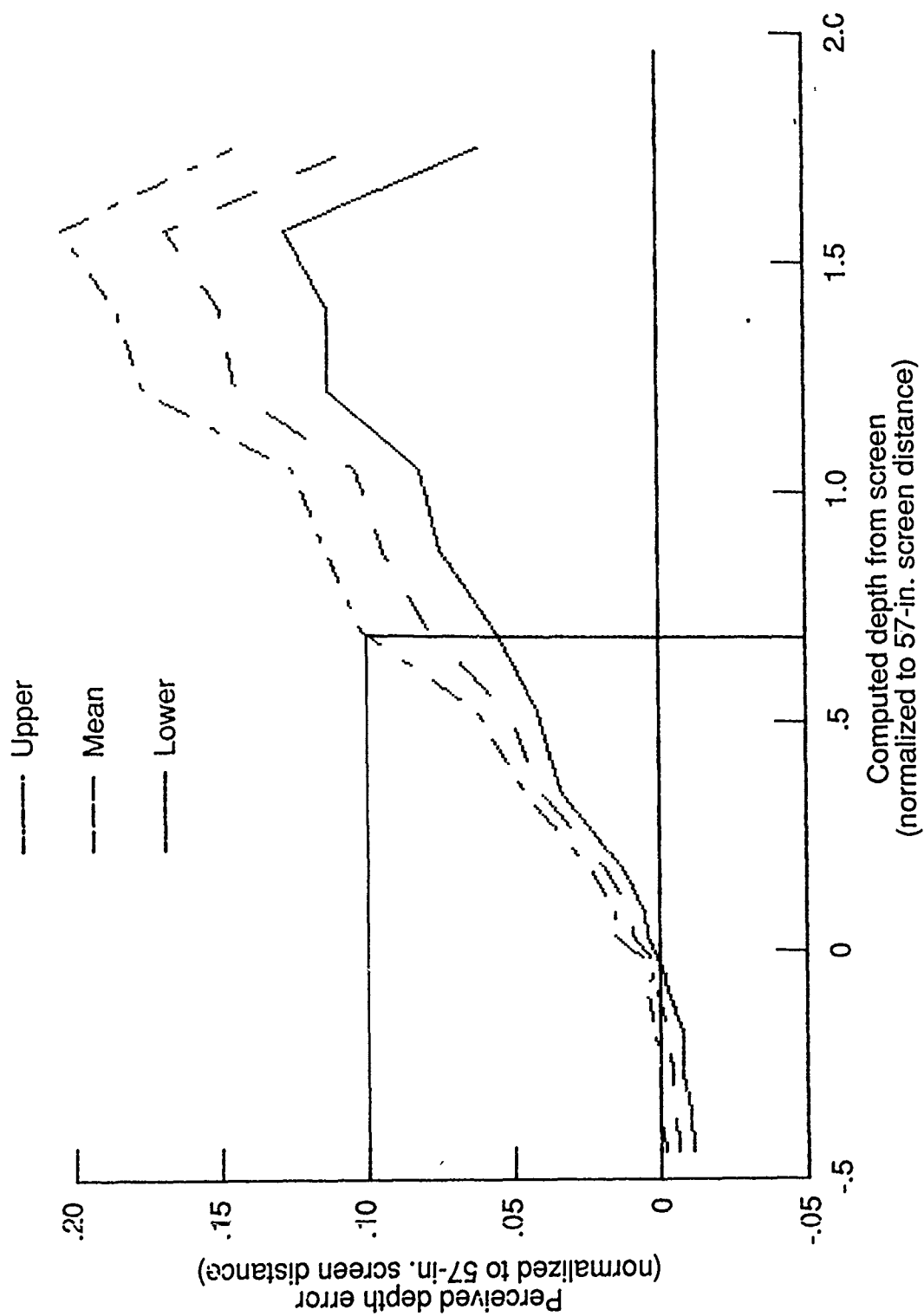


Figure 14. A 95-percent confidence interval for perceived depth error as function of computed depth for screen distance of 57 in.



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16. Abstract Three-dimensional ("real-world") pictorial displays incorporating "true" depth cues via stereopsis techniques offer a potential means of displaying complex information in a natural way to prevent loss of situational awareness and provide increases in pilot/vehicle performance in advanced flight display concepts. Optimal use of stereopsis cueing requires an understanding of the depth-viewing volume available to the display designer. This report presents suggested guidelines for the depth-viewing volume from an empirical determination of the effective region of the stereopsis cueing (at several distances between the viewer and the cathode ray tube (CRT) screen) for a time-multiplexed stereopsis display system. The results provide the display designer with information that will allow more effective placement of depth information to enable the full exploitation of stereopsis cueing. Additionally, the data revealed the fact that increasing the viewer-CRT screen distances provides increasing amounts of usable depth but decreases the fields of view. A stereopsis hardware system that permits an increased viewer-screen distance by incorporating larger screen sizes or collimation optics to maintain the field of view at required levels would provide a much larger stereo depth-viewing volume. (kr) ←					
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